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ABSTRACT

This paper consolidates relevant reliability and maintainability (R&M) information based on documented findings from field installations. Data from government sponsored demonstration projects, utilities, private consultants, and owner surveys are included. Failure rates and problem frequencies are emphasized rather than guidelines and experiences, which have been compiled elsewhere. R&M issues concerning solar energy systems, subsystems, and components are reviewed. The information presented is based upon 20 applicable R&M studies. Whenever possible, analogous data from the various studies are compared and combined to give a clearer, more complete representation of pertinent R&M issues.

1. INTRODUCTION

As a result of the Arab oil embargo in 1973, the U.S. government began to focus attention on the use of solar energy to displace fossil fuel. A number of government-sponsored programs were instituted specifically aimed at demonstrating the feasibility of using solar heating and cooling in residential and commercial buildings. Public interest in solar energy and solar-related tax incentives gave rise to a dramatic increase in the number of private companies engaged in solar system manufacture, marketing, and installation. A number of public utilities across the country also initiated residential solar energy programs (1). The result of these activities was an increase in the number of homes featuring active solar systems in the United States from less than 5000 in 1974 to over 160,000 in 1980 (2).

Since the economics of solar systems depend directly upon the performance of such systems, a number of efforts were made to monitor the operation of selected installations. The level of instrumentation used in these undertakings ranged from Btu-meters to determine energy output (3) to an array of temperature, flowrate, and radiation sensors (4) to yield subsystem efficiencies. In general, the results were discouraging. System efficiencies were often much lower than expected. Major failures were common.

Although some attempts were made to gather reliability and maintainability (R&M) data, this was often done as a secondary effort in a performance study. No broad-based program to acquire R&M data equivalent to the Department of Energy (DOE) and Department of Housing and Urban Development (HUD) attempts in performance monitoring was ever established. As a result, R&M data on solar systems is of varying quality and is scattered throughout the literature.

It is the intent of this paper to consolidate the findings of previous R&M studies into a single document and thereby draw conclusions regarding R&M issues based on the combined data. Emphasis is placed on hard reliability data (e.g., failure rates) as opposed to design guidelines and informal field experiences which have been related elsewhere (5-10).

The important characteristics of the information used for this undertaking are summarized and presented in Ref. 11. Each study considered is identified by the organization performing the work and the number of systems involved. The type of study (monitored sites, on-site inspections, owner survey, etc.), and a subjective classification of the R&M relevancy of the data included in each study are also indicated.

2. COMPARISON OF RELIABILITY OF SOLAR ENERGY SYSTEMS

Very little quantitative data comparing reliability issues of domestic hot water (DHW) versus space heating (SH) versus space cooling (SC) systems was found in the literature. The vast majority of the studies included in Ref. 11 deal with DHW systems only. Studies that contrasted various types of systems contained small data bases (i.e., a small number of systems) making significant conclusions difficult. Other studies that included a large number of comparable systems treated R&M problem incidences on an aggregate basis and did not report separate DHW/SH/SC findings. Thus, this paper concentrates on the various types of SDHW systems.

Applicable reliability data for common SDHW systems are summarized and presented in Table 1 (12-15). For each SDHW system type listed, data extracted from Refs. 12-15 included the number of systems in each study, the percentage of systems experiencing problems, and the average number of problems per system in the study. The totals provide an aggregated picture of the relative reliability of these system types.

Less than a third of the drainback and recirculation systems reported problems. Draindown, air, oil, and electrically heat-traced systems all had very high incidences of problems. More than 80% of each of these systems sustained malfunctions. Antifreeze systems had an intermediate number (59%) of problems.

In terms of the average number of problems sustained per system, drainback and recirculation systems fared extremely well (less than one problem for every two such systems). Antifreeze, air, and oil systems exhibited an intermediate level of problems (1 to 2 problems/system). Heat traced and draindown systems had extremely high occurrences of problems (3.68 and 4.05 problems/system, respectively).

3. RELIABILITY AND MAINTAINABILITY OF SOLAR ENERGY SUBSYSTEMS

The major solar energy subsystems are considered to be collectors, storage, transport, and controls. For over 1000 systems included in the National Solar Demonstration Program (NSDP) (16) operating between 1975-80, the collector and transport subsystems were found to be the most failure prone (Table 2). Approximately 30% of all systems reported problems with these subsystems. The percentage of systems encountering controller and storage subsystem problems was approximately 20%. Almost 60% of all systems experienced troubles of some kind. With the exception of storage, problems at the subsystem level were nearly evenly divided between start-up occurrances and problem incidences after the first year of operation.

In considering the HUD residential NSDP problem incidences as a function of air vs. liquid systems for heating and hot water, Freeborne and Mara (17) report that for air systems, the transport/distribution subsystem was the most failure prone (42% of failures) compared to collectors (23%), controls (21%), and storage (14%). For liquid systems, collectors were the most problem susceptible subsystem (31% of failures) with transport (25%), storage (22%), and controls (22%) being slightly more reliable.

Table 1. Reliability Problems of Common SDHW System Types (12-15)

SDHW System Type	Totals for Studies: # of Systems	% of Systems with Problems	Average Number of Problems Per System
Drainback	25	32	0.40
Draindown	39	85	4.05
Recirculation	63	27	0.33
Antifreeze	95	59	1.42
Air	6	83	1.17
Oil	6	83	1.33
Heat-Traced*	22	100	3.68
TOTALS	256	57	1.64

*Electric resistive heating provided to piping to prevent freezing.

Table 2. Comparison of Subsystem Problem Incidences Reported for 1013 Systems Included in the NSDP (16)

Subsystem	% of Systems Reporting Problems	Total # of Systems Reporting Problems	Total # of Problems Reported	First Year #	First Year %	After First Year #	After First Year %
Collector	30	301	351	164	47	187	53
Transport	31	314	391	224	57	163	43
Storage	19	188	241	96	40	145	60
Controls	20	204	255	142	56	113	44
Totals	59*	598**	1238	626	51	608	49

*From (17) (Freeborne & Mara).

**59% of 1013 total systems.

3.1 Collector Subsystem

A large selection of collector types are available for use in solar energy systems. Ref. 18 provides a comparison of four common designs, namely, liquid and air flat-plates, tracking/concentrating, and evacuated tube collectors. Two-thirds of the liquid flat-plate collector subsystems experienced failures, whereas only slightly more than a third of the air collectors reported problems. Half of the tubular collectors were affected by malfunctions (although only four such collectors were included in the study). Tracking concentrators encountered the greatest percentage of failures with nearly 86% (6 of 7 collectors) reporting problems.

A detailed breakdown of flat-plate collector problem types is presented in Table 3. Data from six studies (14,15,18-21) are assessed and combined to provide a clearer picture of why collectors failed. Over 500 total systems reported 228 problems with flat-plate collectors. Twenty-one percent of all component problems reported in these studies were collector-related.

The greatest incidence of flat-plate collector troubles that occurred involved leaks (26% of all reported collector subsystem problems), damaged glazings (20%), seals and gaskets (15%), and freezing (12%).

3.2 Storage Subsystem

Available R&M data on storage units tends to be either aggregated data (no details are given about the variety of storage subsystems studied; hundreds of dissimilar subsystems are generically categorized as storage) or very specific (600-1000 systems that all use the identical storage subsystem). The former is characterized by the National Solar Demonstration Program (NSDP) data as discussed at the beginning of Section 3; the latter is particularly true of several of the utility demonstration programs (22-25).

Table 3. Types of Flat-Plate Collector Problem Incidences (14,15,18-21)

Problem	Totals for Six Studies	
	#	%
Freezing/burst pipe	27	12
Leaks	60	26
Seals/gaskets-	34	15
Condensation/outgassing	19	8
Insulation	2	1
Glazing damage	46	20
Absorber coating	12	5
Buckling	3	1
Wind	9	4
Design/installation	9	4
Other	7	3
Total incidences	228	—
% of reported problems	21	—
Average # of collector problems per system	0.45	—

Reported failure incidences vary for different types of storage subsystems (liquid vs. air vs. phase change material). Of 100 systems included in Ref. 14, the four air systems showed no storage problems. This is in contrast to the claim elsewhere that air system storage container leakage was found to be a significant problem (19).

Leakage is also a problem in liquid systems. In a recent utility study (15) two out of 18 antifreeze systems (11%) experienced water leaks from the solar storage tank. Slightly improved reliability is suggested by Refs. 20 and 21. Ten of 154 systems (6%) and three of 124 systems (2%) had storage tank fluid leaks.

3.3 Transport Subsystem

A major potential problem attributable to heat transfer fluids is failure to provide adequate freeze protection. Ref. 26 discusses the instances of freezing as a function of the three most common heat transfer fluid systems: air, water, and antifreeze solution. The reliability of freeze protection afforded by water systems is low. The primary mode of freeze-related failures in air systems was thermosiphoning of cold air back to an air-to-water heat exchanger due to leakage of a back-draft damper. A significant number of antifreeze systems did not provide adequate freeze protection either. The primary failure mechanism of antifreeze systems is also thermosiphoning of glycol solution between cold collectors and a warm heat exchanger, causing freezing of the water side of the heat exchanger.

Heat transfer fluids have the potential to cause corrosion of other system components. Fluids that normally afford good corrosion protection (e.g., glycol solutions) can degrade during service conditions and initiate chemical attack of pipes, collectors, heat exchangers, etc. Overheating of collectors with selective absorbers causing propylene glycol to become acidic was identified as a major problem with the Memphis 1000 study during the summer of 1979 (24,25). Thirty-nine percent of the propylene glycol systems in another study (27) that had upper temperature-limit, shut-off control strategies (that allowed collector stagnation) were found to have acidic heat transfer fluids (pH < 6.5).

Fluid passageways provide the means for allowing the heat transfer fluid to circulate between the collector subsystem and the storage subsystem. This refers to duct work for air systems and piping for liquid systems. Piping was found to be the second most failure-prone component of solar collection systems (after controls) during a recent R&M directed study (28). Refs. 12 and 13 also found leaks to be the second most prevalent problem encountered (after controllers).

The driving force for fluid circulation in solar energy systems is typically provided by fans for air movement and pumps (centrifugal) for liquid flow. Air handlers have generally been reliable components, although malfunctions have been reported. Pump problems exhibit an interesting correlation between the frequency of problems encountered and the time period during which the studies were conducted. Table 4 lists the relevant studies chronologically and provides the percentage of pump failures. The trend of the percentage of systems reporting pump failures with time is clearly evident. As can be seen, early studies indicate high percentages of failures (20%-35%), whereas later studies show much higher reliability.

3.4 Controls Subsystem

High failure rates with controls subsystem components have been frequently experienced in the solar industry since its inception (21,22). Controller components considered in this section include the control hardware unit (controller), control strategy, sensor leads, and temperature sensors.

Controller hardware evidenced the greatest incidence of problems reported in Ref. 19; design and control settings were secondary effects. Controllers were by far the most failure-prone component of the 16 solar systems investigated in Ref. 28. This theme was recurrent in other studies as well.

Problems with temperature sensors are nearly as prevalent as controller malfunctions. Nearly identical overall problem incidence percentages for sensors (6%-7%) as reported in Refs. 12-14, 24 and 25. Other studies showed reduced, although substantial, sensor problems relative to controllers.

In general, sensor placement and installation are seen to be more critical than inherent faults with the component itself. Most of the installer-caused control failures are due to improper attachment or abuse of the sensors (21). Factory installation of sensors is greatly desirable for improved component reliability.

4. COMPARISON OF RELIABILITY OF SOLAR COMPONENTS

In this section, aggregated problem incidences of various solar elements are considered to provide an intercomparison and ranking of the relevant solar system constituents.

Table 4. Chronology of Pump Problem Rates

Dates of Study	% of Systems Reporting Pump Problems	References
1973-78	21.0	25
1975-76	23.0	17
1976-80	35.0	22
1978-79	33.0	23,24
1978-80	11.3	26
1978-82	5.4	27,29
1979-82	4.4	30,31
1981-82	1.5	15,16

The problem incidences for eight applicable studies (12-15,18-21,28) have been incorporated in Fig. 1. From the figure it can be seen that piping/ducts, controls, and collectors have relatively high percentages of problem incidences. Pumps and fans and valves and dampers are intermediately reliable. Storage units and heat exchangers appear to be the most reliable solar components.

5. CONCLUSIONS

The following conclusions and recommendations have been formulated based upon the evaluation and assessment of historical R&M data found in the literature.

A comparison of the reliability of solar systems revealed:

- Based on a small number of comparative systems, DHW-only systems are relatively more reliable than combined SH + DHW systems.
- Liquid systems are, in general, less reliable than air systems. However, it should be noted that the nature of air systems makes failures difficult to detect (leaks go unnoticed and do not cause damage). Such problems can only be characterized in terms of a degradation in system performance.
- Of the liquid systems, drainback and recirculation systems are fairly reliable, antifreeze and oil systems are intermediately reliable, and draindown systems and systems with electric resistance heating to prevent freezing are the least reliable of the systems studied.

Evaluation of solar subsystems disclosed:

- Collector subsystems have low reliability; 30%-50% of the systems surveyed reported collector problems of some type.

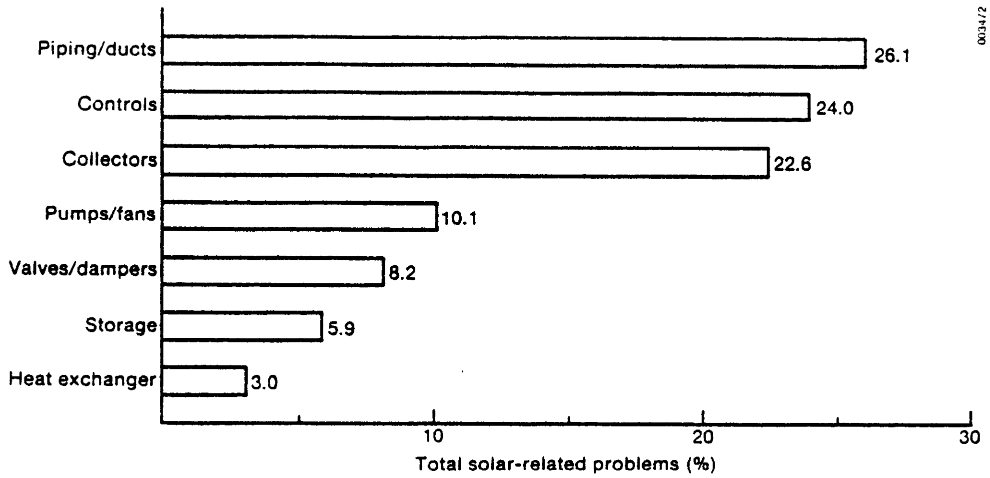

Figure 1. Relative Reliability of Solar Components Based on Aggregated Data (652 systems)

- Problems experienced by flat-plate collectors that need to be further addressed include leaks, damaged glazings, seals and gaskets, and freezing.
- Storage subsystem problems tend not to be severe, and the impact on system operation appears to be minimal.
- Proper attention paid to design and installation guidelines should result in very reliable storage subsystems.
- Although no single heat transfer fluid exhibits all of the desirable properties such a fluid should have, most are capable of functioning properly if their limitations are recognized and taken into consideration during system design, installation, and operation.
- Many problems with fluid passageways have been documented, but strong evidence suggests that many fluid channel failures can be eliminated by improved installation practices.
- Control subsystems experience fairly high incidences of problems although the level of severity tends to be low.
- Temperature sensor placement and installation are more critical than inherent faults with the component itself.

Concerning the relative reliability of solar components it can be concluded (Figure 1) that:

- Piping/ducts, controls, and collectors exhibit relatively poor reliability and require further R&M research. Although piping and ducts exhibited the lowest reliability of the solar components considered, problems tended to be installation-related (avoidable) and generally less severe (typically easily repairable leaks) than problems with other components.
- Pumps and fans and valves and dampers are intermediately reliable.
- Storage units and heat exchangers appear to be the most reliable solar components.

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